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A Novel Reconfigurable Ultra-broadband Millimeter-wave Photonic Harmonic Down-converter

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***Abstract*—We propose a novel ultra-broadband reconfigurable photonic harmonic mixer functioning as a millimeter-wave down-converter for multigigabit wireless applications. Based on frequency conversion implemented by an optical frequency comb generator, the photonic mixer is able to operate up to 100GHz without high frequency RF components. The feasibility of the approach is experimentally validated by down-converting an up to 5Gbps fiber-wireless quadrature phase shift keying (QPSK) signal from W-band (102.5GHz) to S-band (2.5GHz). The frequency response and the conversion efficiency are investigated. The experimental results show that the bandwidth of the proposed mixer is highly reconfigurable by adjusting the frequency comb generator.**

Keywords—Microwave photonics; fiber wireless communication; radio-over-fiber, harmonic mixer

I. INTRODUCTION

The development for multigigabit capacity wireless systems is driven by the increasing demand of bandwidth intensive applications, e.g. uncompressed high definition video signal transmission and high speed internet, etc [1]. Radio-over-Fiber (RoF) technology provides elegant solutions for even higher bandwidth requirements beyond ~Gb/s thanks to the ultra-wide bandwidth and agility characteristics of photonic devices [2]. Therefore, multigigabit RoF links operating at ultra-high RF frequency (E-band/60-90GHz or W-band/75-110GHz) are under intensive investigation in these years [3]-[5]. As Fig.1 shown, an indoor hybrid fiber-optic / wireless system implemented via RoF technology is a candidate for future multi-services access system deployment. For the consideration of cost efficiency, indoor wireless access points serve as basic optical/electrical (O/E) or electrical/optical (E/O) conversion modules and the ultra-high frequency fiber-wireless signal is transmitted to a central office for demodulation. In the central office, one of the key issues is down-conversion of RF carrier from ultra-high frequency to the applicable frequency range of receiver front end. Traditional fiber-wireless down-converter relies on electrical mixing resulting in inevitable usage of costly ultra-broadband photodiode and mixer, which becomes unpractical for even higher carrier frequency. Therefore, in the development of fiber-wireless down-conversion technique, it is of great interest to find simple solutions alternatives to the often complex conventional electrical methods to detect vector modulated signals when the bit rate increases and RF carrier approaches to W-band or even higher. Recently, several efforts has contributed to demodulate millimeter-wave (mm-wave) fiber-wireless signals using digital coherent receiver structures [6], [7], but additional components such as optical oscillator and high frequency analog digital converter (ADC) are inevitable. Additionally, coherent detection combined with baseband digital signal processing (DSP) receiver has also been proposed [8], although the proposed structure doesn't require high frequency RF components or ADCs, it is still not fully flexibly reconfigurable to support a wide range of multiple frequency bands.

In this paper, we propose a novel reconfigurable photonic harmonic mixer as a mm-wave down-converter that can be applicable to demodulate high frequency signal in different mm-wave bands (e.g. 60GHz, 70/80GHz and 100GHz). The photonic harmonic mixer is based on an optical frequency comb generator implemented by cascaded phase modulators (PMs). The high-frequency fiber-wireless signal is spectrally copied with the spacing of the comb fundamental frequency. The intermediate frequency (IF) signal can be obtained after heterodyne beating of identical copies of original signal. The output of the mixer includes two switchable IFs which can be selected in the digital domain. The proposed approach shows a uniform frequency response and reconfigurable bandwidth characteristics due to the frequency flexibility of comb genneration. The error vector magnitude (EVM) performance of carried QPSK signal is studied as well, showing 5% EVM

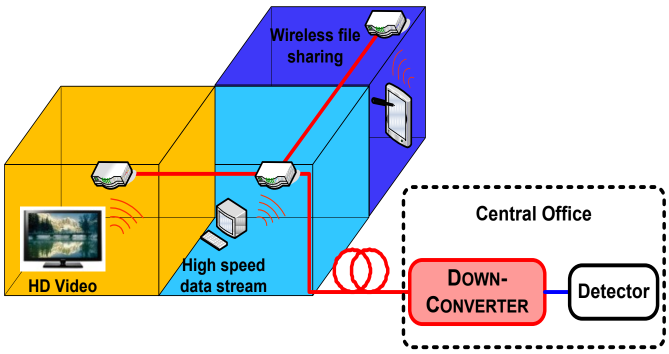

Fig. 1. A hybrid fiber-optic / wireless access system with multi-applications in indoor environment. The fiber-wireless signal is down-converted in the central office.

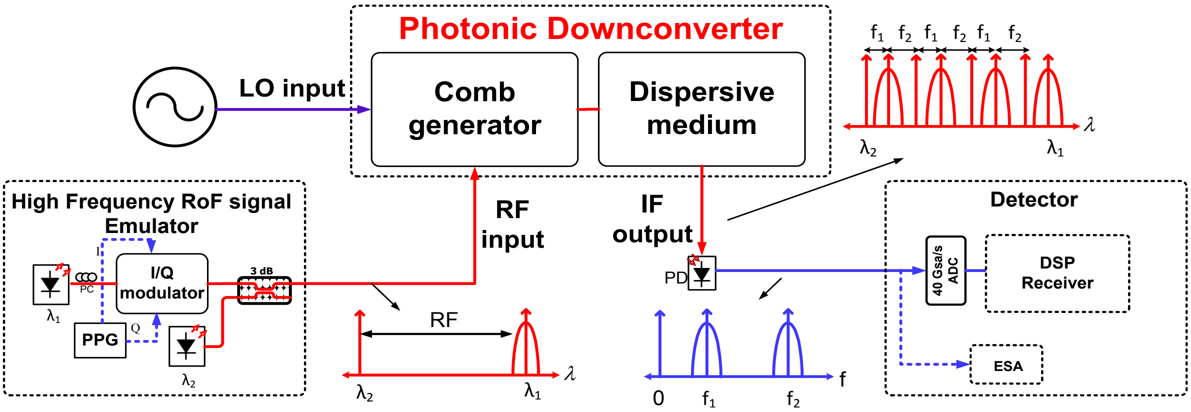

Fig. 2. Experimental demonstration setup (PPG: Pulse pattern generator, ADC: Analog digital converter, ESA: Electrical signal spectrum analyzer)

degradation when increases the carrier frequency from 60GHz band to 100GHz band.

II. Experimental Setup and Principle

As shown in Fig. 2, the proposed photonic harmonic mixer consists of an optical comb generator, a piece of dispersive medium and a low-cost p-i-n photodiode (PD) with 10 GHz bandwidth. The comb generator composed of two consecutive phase modulators [9] is driven by a radio frequency (RF) carrier at f_0. It can be clearly observed that when the optical millimeter-wave signal with λ_2 central wavelength and λ_1 side-band wavelength is launched into the mixer, the comb generator will create a plurality of comb lines of optical input signal, which have fixed frequency separation, corresponding to the driven RF signal f_0. And the comb lines of side-band wavelength will interleave with the comb lines of central wavelength. In this way, by using a low-bandwidth PD, the high frequency of RF signal can be downconverted to two different intermediate frequencies (IFs) f_1 and f_2, as shown in Fig. 2. Moreover, f_1 and f_2 should satisfy the Eq. (1).

$$f_{RF} = \left\lfloor \frac{f_{RF}}{f_0} \right\rfloor \times f_{RF} + f_1 \qquad (1)$$
$$f_1 + f_2 = f_0$$

Where f_{RF} is the frequency of the millimeter-wave signal, and the f_0 is the driven RF carrier frequency of the optical comb generator. The dispersive medium between optical comb generator and PD is used to convert optical phase information into optical intensity. It should be noticed that as the heterodyne beating between each pairs of the adjacent side-bands result in the same frequency f_1 and f_2, they will overlap with each other in the electrical domain and hence enhance the power of the received signal. Therefore, the more comb lines of the input signal are generated from the optical comb generator, the more heterodyne beating side-bands will be, leading to the better receiver sensitivity.

The schematic of the experimental setup is shown in Fig.2. Millimeter-wave fiber signals are emulated by using the heterodyne method. An optical carrier is emitted from an external cavity laser (ECL, λ_1=1550 nm). It is then fed into an optical I/Q modulator, where two independent data streams

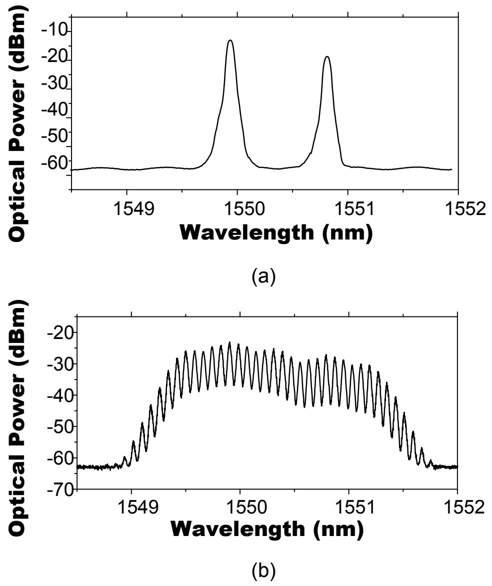

Fig. 3. The optical spectra of the emulated RoF signal before (a) and after (b) the comb generator

(pseudo random bit sequence with a word length of 2^{15}-1) are used to modulate the input optical carrier and the optical QPSK signal is obtained at the output of the modulator. After that, an un-modulated continuous wave (CW) carrier tunable central wavelength λ_2 is generated from a second ECL and combined with the optical QPSK signal. The second CW carrier λ_2 in this case mixes with the first wavelength, and turns the optical QPSK signal into a RoF QPSK signal with RF carrier frequency equals to the frequency difference between the two optical carriers. Therefore, the RoF signal emulator can be seen as a RoF QPSK signal generator with tunable RF frequency. It should be noted that the linewidths of these two optical carriers are several MHz, and they are incoherent, which results in the quality degradation of the generated RoF signal compared with the traditional millimeter-wave over fiber signal. The reason is that in the traditional optical millimeter-wave generation [10, 11], the optical phases of optical carrier and the side-band RF signal after modulation are correlated as they are from the same laser source [12]. But in our scheme, the heterodyne beating between the two optical carriers will generate a RF signal with

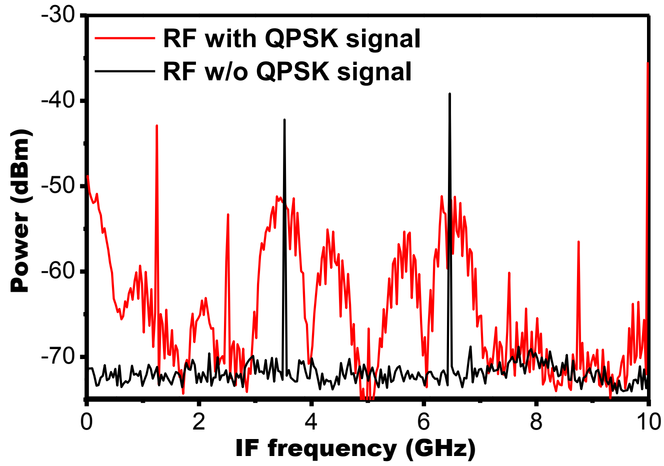

Fig. 4. Electrical spectra of the down converted RoF signal with and without QPSK modulation

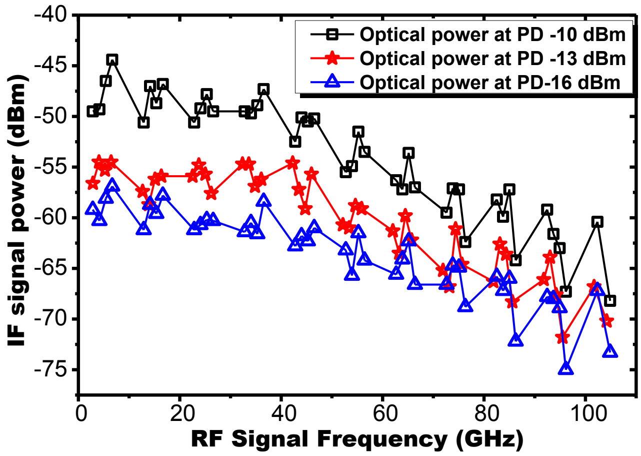

Fig. 5. Frequency response of the photonic down-converter as a function of the received RoF signal frequencies

relatively higher phase noise. Therefore, this RoF signal emulator is only for experimental demonstration purpose as the RF frequency in this emulator can be widely adjusted. In real RoF system the signal quality is expected to be better.

The optical spectra of the emulated RoF signal at the output of the emulator is shown in Fig. 3 (a) when λ_2=1549.6 nm. The optical comb generator in our proposed photonic mixer is driven by a 10 GHz RF source therefore the gap between the adjacent comb lines is f_0 = 10 GHz, corresponding to 0.08 nm in the optical spectrum. Fig. 3 (b) shows the spectra of the output signals from the comb-generator, we can clearly observe that the comb lines of the input optical signal λ_1 and λ_2 are interleaving with each other. The electrical spectra of the downconverted RF signal at the output of the PD with and without QPSK modulation are shown in Fig. 4, respectively. During this measurement, the RoF signal emulator is adjusted to generate a RF frequency of 62.5 GHz and the optical power at the PD is -13 dBm. It can be seen that we can get two different RF signals f_1 and f_2, which are symmetrical with 5 GHz. In the case without QPSK modulation, the two pure RF carriers have around -40 dBm peak power. For the QPSK RF signal, except for the RF signal spectrum, we can also see baseband signal, which is introduced by the self-beating of the comb lines of the side-band RoF signal. The signal power at both frequencies is almost the same. Therefore, we can obtain the demodulated signal from each of them.

For QPSK signal receiving and demodulation, the output RF signal from the PD is sampled by a 40 GSa/s ADC with analog bandwidth of 13 GHz. After that, the digital signal is demodulated by a digital signal processing (DSP) receiver which includes algorithms for band pass filter (BPF), frequency offset compensation, downconvertion, and timing synchronization before the bit error rate (BER) decision.

III. Results

Fig. 5 shows the frequency response curves of the optical down-converter. The received IF signals as a function of emulated RoF signal frequency are shown for different received optical power into the PD. It can be seen that as the RF frequency increases, the trend for the received IF power decreases. The reason is that the higher frequency the emulated RF is, the larger the corresponding separation between optical carriers (λ_2 and λ_1) becomes. Therefore, the number of interleaved side-bands between these two wavelengths after the comb generator is comparable smaller than that of when the separation is smaller or the RF frequency is lower due to the number limitation of the comb lines in the optical comb generator. Consequently, fewer signals' side-bands take part in the heterodyne beating, causing a decrease of received IF signal power. It can also be seen from Fig. 5 that at certain frequencies there are power peaks or valleys. The reason for this phenomenon is that we choose and stick to one of the two generated IF signals when measuring its peak power. Therefore at certain RF frequencies the tested IF signal is smaller than 5 GHz and at others it is larger than 5 GHz. As the responsivity of the PD is not perfectly flat, which in fact has better response at lower frequencies, there are differences in received IF power with regard to different down-converted IF frequencies. Nonetheless, the overall trend of the frequency responses is in accordance with each other. Moreover, from this figure we can observe that there is approximately 15 dB power decrease for all the three curves in the frequency range from close to 0 GHz up to more than 100 GHz. More interestingly, we can also notice the weak IF output power is expected to be tackled by increasing incident optical power into the PD.

The EVM performances as a function of RoF QPSK signal data rate for different RF frequencies at 62.5 GHz, 82.5 GHz and 102.5 GHz are shown in Fig. 6. During this test the optical power received at the PD is – 10 dBm. First of all, it can be observed that as the RF frequency increases, the received signal EVM becomes larger. This is because the signal power becomes smaller when the RF frequency increases, as shown in Fig. 5, which results in a smaller signal noise ratio (SNR) compared with lower frequency RF signals. Secondly, we can see that when the data rate is smaller than 2.5 Gbps, there is negligible difference between the EVMs for the same RF frequency; when the data rate reaches 5 Gbps,

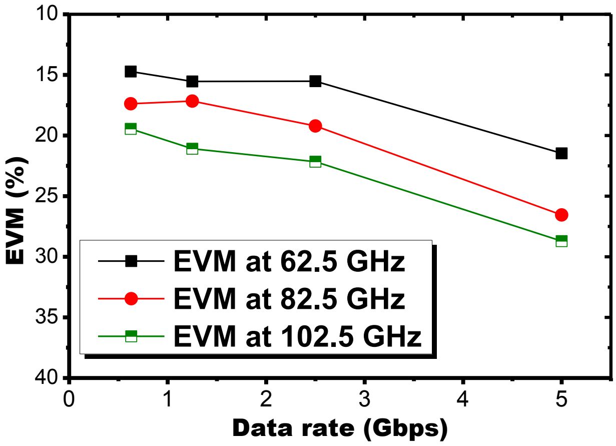

Fig. 6. EVM of the detected QPSK signals after down-conversion as a function of data rates for different RoF signal frequencies

there is approximately 7% increase in EVM for each RF frequency, respectively. This is because larger bandwidth signal is more sensitive to linewidth and frequency stability. Furthermore, it can be seen that for data rate up to 5 Gbps with RF frequency of 102.5 GHz, the best EVM is smaller than 30%, which means this down-converter can give us acceptable conversion efficiency for 100 GHz millimeter-wave signal detection. In particular, it is noted that the bandwidth of the proposed photonic harmonic mixer is mainly determined by the comb spacing in the optical comb generator. In the experiment, we proof-of-concept demonstrated a 10GHz comb generator, and hence a more broadband photonic mixer is reasonably achieved by adjusting the comb spacing.

IV. Conclusion

We propose a novel photonic harmonic down converter for broadband millimeter-wave signal detection by using an optical comb generator. We experimentally tested our proposed photonic harmonic down-converter in 60 GHz, 80/90 GHz and 100 GHz bands down to lower than 10 GHz. In addition, frequency response of our proposed photonic down-converter is tested from several GHz up to more than 100 GHz. An emulated 5 Gbps QPSK RoF signal at carrier frequency of 102.5 GHz is successfully down-converted and demodulated using our proposed method for demonstration purpose. The proposed photonic down-converter is fully reconfigurable and it can realize frequency down-conversion in full mm-wave bands with tunable wide bandwidth. Moreover, no high frequency photodiode, complex RF components or expensive ADCs working at high frequency is needed. This novel high frequency down-converter can be seen as one of the promising candidates that have the potential to play important roles in future ultra-broadband millimeter wireless communication systems.

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